H′ and χ, on the one hand, and H′ and χ^{-1}, on the other, are precisely the same, so that we may write

$$H = \chi' \, . \, H' \, . \, \chi'^{-1}, \tag{19}$$

with permissibility of interpretation as in (18).

Similarly from (18) and (19) by means of (5) of § 7

$$L' = (m^{-1}\chi) \, . \, L \, . \, (m\chi^{-1}), \tag{20}$$

$$L = (m\chi^{-1}) \, . \, L' \, . \, (m^{-1}\chi), \tag{21}$$

with the same permissible interpretation as to the incidence of the application of the differentiations of L and L′ on the right; they may be supposed to affect the immediately following $(m\chi^{-1})$ and $(m^{-1}\chi)$ or not, at our pleasure.

A New Form of Wehnelt Interrupter.

By F. H. Newman, M.Sc., A.R.C.Sc.

(Communicated by Lord Rayleigh, F.R.S. Received February 21, 1921,—Received in revised form, March 18, 1921.)

[Plates 3 and 4.]

1. *Introduction.*

The original form of Wehnelt Interrupter has many disadvantages. Unless special precautions for cooling the apparatus are taken, the solution soon boils, and the interrupter ceases to work. The large current density causes rapid disintegration of the platinum wire, and there is considerable expense in renewing it. The interrupter cannot be used with alternating currents owing to the melting of the wire when it is the cathode.

Sulphuric acid has a fairly large electrical conductivity, compared with other electrolytes, and the mean value of the current density at the wire electrode is large. There is, as a result, considerable heat developed in the volume of the acid. If a high resistance electrolyte is substituted, the current density at the platinum wire is much smaller, and the heating effect is reduced. The fumes arising from the acid, and also the spraying, when the interrupter is in action, are objectionable.

Although electrolytic interrupters are not widely used in the laboratory, they are in considerable demand for X-ray work, because of the heavy disruptive discharges which are obtained in the secondary of a coil operated by these interrupters. Providing special arrangements are made for the cooling, they require very little attention, and the interruptions are very steady and regular. The new form of Wehnelt Interrupter described below has many advantages over the older form.

2. *Description of New Form of Interrupter.*

The anode consists of a platinum wire which protrudes from a glass or porcelain tube. It is capable of adjustment by means of a threaded rod to which it is attached. A milled head is fixed to the rod, and so, by screwing up or down, the amount of the platinum surface exposed to the action of the electrolyte can be varied. In this way the platinum wire can be renewed without dismantling the apparatus; also the mean value of the current can be altered. The anode consists of an aluminium vessel which contains the electrolyte. The vessel thus serves a double purpose, and is more portable than a glass vessel. The electrolyte is a saturated solution of ammonium phosphate. If the solution is unsaturated, the interrupter works well, but requires a higher applied potential difference before the interruptions commence. This electrolyte has a very high specific resistance, and the current density at the wire is much lower than in the old form of Wehnelt Interrupter. As a result there is less local heating in the neighbourhood of the platinum, and less disintegration. Aluminium, with the ammonium phosphate, confer rectifying properties on the interrupter. The current will pass only from the wire to the aluminium in the solution, and, when alternating currents are employed, one-half of the wave is suppressed. Thus the wire never becomes the cathode, and there is no disintegration. No acid fumes are emitted, and even at 90° C. the interruptions are steady and regular. The older form of Wehnelt Interrupter ceases to act at this temperature. There is no fatigue of the platinum wire in this modified form.

3. *Experimental Results with the Modified Form.*

Table I shows the results obtained when the surface area of the wire exposed to the electrolyte was altered. The applied potential difference was that necessary to start the interruptions. The current increases as the surface area increases, but the current density remains constant. As the surface area increases, the applied potential difference necessary to start the interruptions also increases, and is proportional to the mean value of the current.

Table I.

Mean value of current.	Applied P.D.	Surface area of wire.	Current density.
ampères.	volts.	sq. mm.	ampères per sq. mm.
12·6	68	88	0·14
10·8	64	81	0·13
8·1	60	74	0·11
6·1	50	57	0·11
4·5	44	39	0·12
2·9	36	23	0·13
2·0	34	15	0·13
1·1	28	7	0·15

Table II indicates that the applied potential difference necessary to start the interruptions decreases as the temperature of the electrolyte increases. Providing the temperature is not too great—above 90° C.—it is advantageous to have the electrolyte hot. The mean value of the current decreases as the temperature rises, but this is due to the decrease in the applied potential difference.

Table II.

Temperature.	Applied P.D.	Mean value of current.
° C.	volts.	ampères.
18	52	6·6
32	44	6·4
45	34	6·2
65	26	6·1
69	23	6·0
78	18	5·7
93	16	5·6
96	15	5·5

4. *Wave Form of Primary Current.*

The wave form of the primary current was investigated by means of oscillograms. The oscillograph used was a Duddell permanent magnet type, having two vibrators specially stretched, so that they were able to follow the variations in the current up to 500 interruptions per second. The resulting curves were photographed by means of a falling plate camera, the speed of the plate at the instant of photograph being about 400 cm. per second. One of the vibrators—in series with a high non-inductive resistance—was placed in shunt with the main current; the other, with a non-inductive resistance in series, was connected across the terminals of the interrupter. In this way it was possible to observe on the same oscillogram, the form of the primary current, and also the variation of the potential difference across the interrupter. The resultant curves are shown in the Plate, the unequal brightness being due to the use of an alternating current arc as the source of light.

With direct currents the interruptions are extremely regular, both as regards frequency and the amount of current interrupted. The rate of decrease of the current at interruption is not uniform, but is very great at the commencement. As a result, the peak value of the potential difference across the terminals of the interrupter is very great—more than six times the mean value of the potential difference as measured on a direct reading voltmeter. The secondary discharge is thus made very disruptive. The ordinary gas bulb used for the production of X-rays, requires a secondary current of large peak value for good working. It is only the peak value of the current which is active, the rest of the current merely producing a heating effect in the bulb. The latter also works well with high frequencies, providing the frequency is not so great that the rate of make of the primary current becomes great. If this is the case, then there is a considerable reverse current in the bulb. Plate 3, I, shows that the time interval of break, compared with the time interval of make, is very small. There is little reverse secondary current. The peak value of the potential difference across the terminals of the interrupter is very great, even when the secondary current is flowing. This is the case also with large frequencies of interruption. The time interval of break is small compared with that at make, and, as a result, the secondary discharge is unidirectional at high frequencies. This is shown in No. II; not all of the current is interrupted, and the greater the frequency the less is the fraction of current interrupted. There is no trace of oscillations in the primary current at break, but, as the current never reaches zero, the conditions are against the detection of oscillations.

With alternating currents there is rectification, one half of the wave being practically suppressed. There is never complete interruption. The modified form works steadily without any self-induction in the circuit. Oscillations in the primary current of an electrolytic interrupter have not been observed previously, and it has been concluded that the gas of polarisation plays no part in the interruption of the current. Plate 3, III, shows decided ripples in the rectified and interrupted portions of the current. These oscillations are present only when there is no self-induction in the circuit. The introduction of self-inductance into the primary circuit changes the wave form of the primary current, increases the frequency of interruption, and decreases the fraction of the current interrupted. This is shown in IV. The secondary current affects the primary current, increasing the frequency of interruption, and decreasing the fraction of current interrupted, V. When the frequency is large—700 interruptions per second—the form of the primary current is irregular, and the interruptions are not equally distributed throughout the half-wave, being more frequent in the first half than in the second half (Plate 4, VI).

Although the loss of one half of the current by rectification means a loss of energy, the heating effect in the interrupter is reduced. When sulphuric acid is used, interruptions take place in both halves of the primary current. but the amount of current interrupted is very small, and varies in the two halves (VII).

As the secondary current in the coil was not great enough to produce a suitable deflection in the oscillograph, it was sent through an air transformer, and the transformed current passed through one of the vibrators. In this way, the wave form of the secondary current, produced under various conditions, was investigated. No. VIII shows the result obtained when a discharge tube was placed in the secondary circuit. The peak value of the current is great compared with the average value. There is practically no reverse current. If the old type of interrupter is used with alternating currents, the secondary discharge is also alternating. This is shown in IX. When the new form of interrupter is employed with alternating currents, the secondary discharge is practically unidirectional, as indicated in X, which represents the result obtained with the secondary current when it is passed through a gas X-ray bulb.

DESCRIPTION OF PLATES.

Plate 3.

The coil was 10-in. spark gap with variable primary. Induction about 1000 henries with a current of about 1 milliampère.

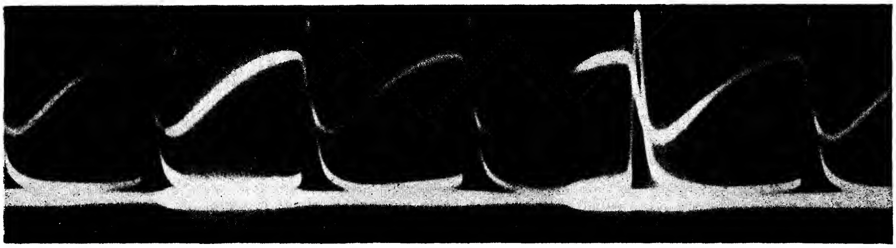
I. New form of interrupter. Direct current in primary. 60 volts, 7·4 ampères. No secondary current. Current and potential difference curves.

II. New form of interrupter. Direct current in primary. 60 volts, 7·0 ampères. Secondary current through spark gap 6-in. Current and potential difference curves.

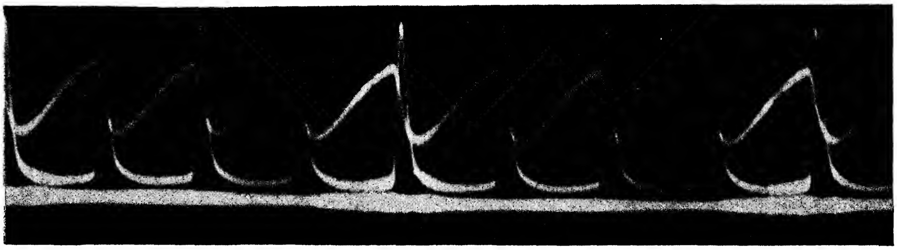
III. New form of interrupter. Alternating current through interrupter only. 100 volts, 4·0 ampères.

IV. New form of interrupter. Alternating current through primary of coil. 100 volts, 6·0 ampères. No secondary current.

V. New form of interrupter. Alternating current, 100 volts, 7·0 ampères. Secondary current through 6-in. gap.



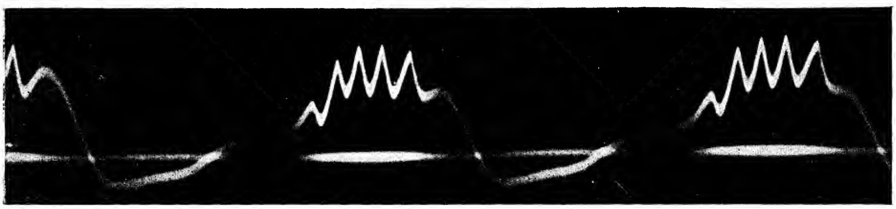
i



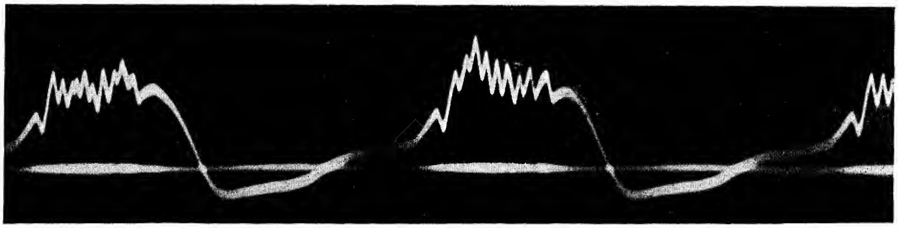
ii

iii

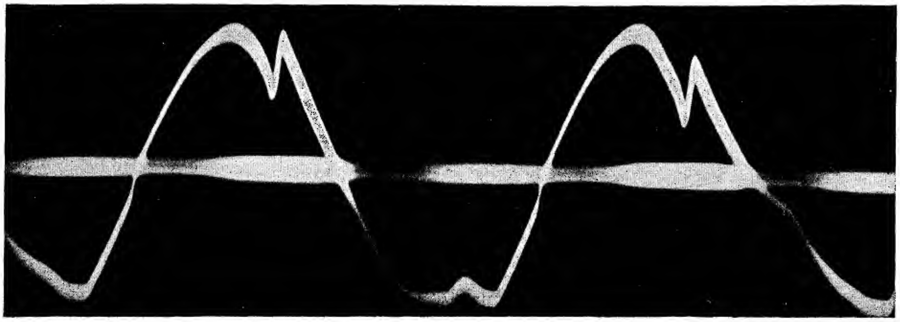
iv



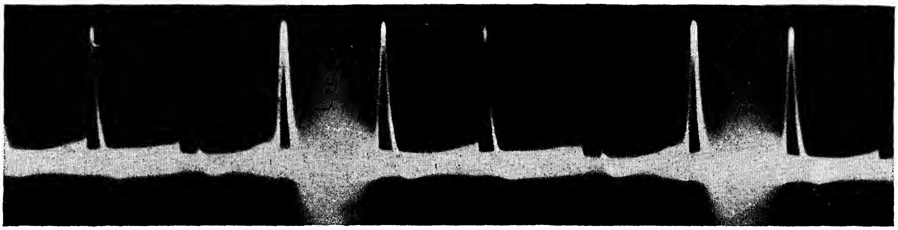
v



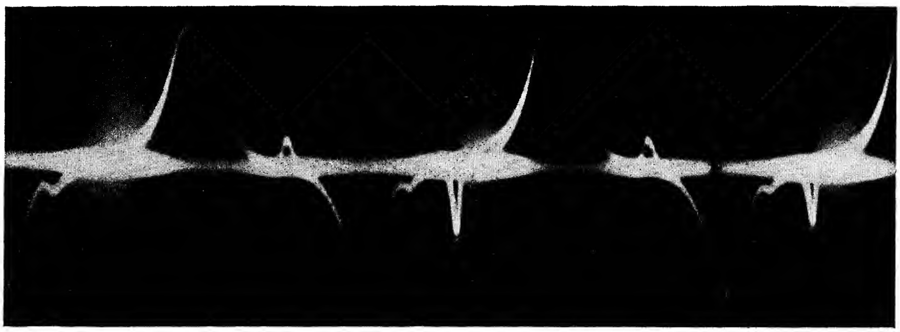
vi



vii



viii



ix

x

PLATE 4.

VI. New form of interrupter. Alternating current, 100 volts, 3·0 amperes. Secondary current through 4-in. gap.

VII. Old form of interrupter. Alternating current, 60 volts, 8·0 ampères. No secondary current.

VIII. New form of Interrupter. Curve of secondary current through discharge tube. Peak value of current 98 milliampères. Mean value 14 milliampères. Direct current in primary, 70 volts, 8·0 ampères.

IX. Old form of interrupter. Curve of secondary current through discharge tube. Alternating current in primary. 60 volts, 8·0 ampères.

X. New form of interrupter. Curve of secondary current through X-ray gas bulb. Alternating current in primary. 100 volts, 8·0 ampères. Peak value of secondary current 180 milliampères. Mean value 5 milliampères.

5. *Discussion of Results.*

The theory of the electrolytic interrupter is less known than that of the mechanical type. A relatively large resistance exists between the wire electrode and the electrolyte. This has been explained by Simon* on the supposition that the large current density causes vaporisation of the liquid in contact with the platinum wire, this layer of vapour forming the high resistance. Blondel† has indicated that the collection of oxygen gas, liberated by electrolysis, accounts for the resistance. He reproduced some oscillograph curves showing, that at 40 periods per second, the current is first established as in all inductive circuits. The electrolysis increases till a gaseous envelope is produced round the anode. Then there is a sudden interruption of the current, and, at the same time, an enormous increase in voltage. Then both the current and the pressure reassume their initial values, and the action begins agains. Blondel states that the energy $\frac{1}{2}LI^2$ accumulated in the self-induction, and liberated by the interruption of the current, causes the condenser formed by the polarised anode in the electrolyte to be charged at high potential. This condenser destroys itself by discharging in an arc which is formed between the platinum and the electrolyte, and drives away the dissociated oxygen. The oscillograph he used did not lend itself to an examination of the action at high frequencies but the oscillograms obtained in the present work, show that the phenomenon preserves the same character whatever the frequency. The value of the induced potential difference in the present experiments, as deduced from the oscillograms, amounts to 500–600 volts, so that the spark discharge can occur.

With alternating current, self-induction is not required in order to obtain the interruptions, and the fraction of the current interrupted is greater

* Wiedemann, 'Annalen,' vol. 68 (1899).

† 'Comptes Rendus,' vol. 128 (1899).

when self-induction is not present. Then, the disruptive force across the gaseous layer is small, and, as a result, the current remains steady, at interruption, for an appreciable interval before it is made again (III).

The oscillograms show that the time interval of interruption is very small. Kallir and Eichberg* applied a stroboscopic method to determine the time interval of interruption, and found it to be of the order 0·0005 sec.; and making further stroboscopic observations, using the platinum-point first as anode and then as cathode, they found that the time interval with a point anode is about double that corresponding to a point cathode.

In the present experiments the gas, which was liberated at the anode, was collected, and found to consist of oxygen 80·2 per cent., and hydrogen 19·8 per cent. by volume. The disruptive spark which passes across the gaseous envelope, must cause some dissociation of the water vapour present, and this explains the presence of hydrogen. There is a copious volume of gas given off at the anode. If the insulating layer consisted of vapour, partial condensation would take place before these bubbles reached the surface of the liquid. This does not appear to occur.

It is probable that the heat effect and electrolysis together account for the production of interruptions.

6. *Summary.*

1. The new form of electrolytic interrupter consists of a platinum wire immersed in a saturated solution of ammonium phosphate. The whole is contained in an aluminium vessel, which sets as the cathode.

2. The current density at the anode is only one quarter of the value in the old form of Wehnelt Interrupter. Consequently there is less heating of the electrolyte, and less disintegration of the platinum wire.

3. The interrupter can be used with alternating currents, which it rectifies.

4. The secondary discharge, obtained with the new type of interrupter is very disruptive. It has a large peak value.

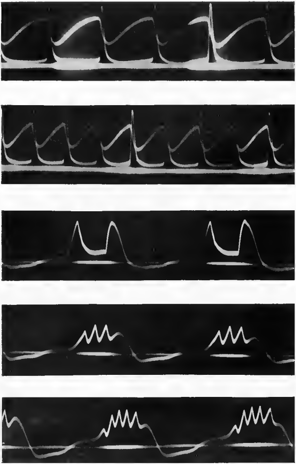
5. This modified type of interrupter works without self-induction in the circuit, when used with alternating currents.

6. The primary current wave form has been investigated with direct and alternating currents.

7. *Conclusion.*

Part of the cost of the apparatus used in the experiments described above has been defrayed by a Government grant, through the Royal Society, for which the author wishes to express his sincere thanks.

* 'Zeitschr. Electrotechn. Wien,' vol. 17 (1899.)



i

ii

iii

iv

v

PLATE 3.

The coil was 10-in. spark gap with variable primary. Induction about 1000 henries with a current of about 1 milliampère.

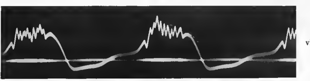
I. New form of interrupter. Direct current in primary. 60 volts, 7·4 ampères. No secondary current. Current and potential difference curves.

II. New form of interrupter. Direct current in primary. 60 volts, 7·0 ampères. Secondary current through spark gap 6-in. Current and potential difference curves.

III. New form of interrupter. Alternating current through interrupter only. 100 volts, 4·0 ampères.

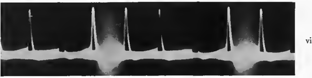
IV. New form of interrupter. Alternating current through primary of coil. 100 volts, 6·0 ampères. No secondary current.

V. New form of interrupter. Alternating current, 100 volts, 7·0 ampères. Secondary current through 6-in. gap.

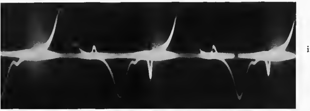


vi

vii



viii



ix

x

PLATE 4.

VI. New form of interrupter. Alternating current, 100 volts, 3·0 ampères. Secondary current through 4-in. gap.

VII. Old form of interrupter. Alternating current, 60 volts, 8·0 ampères. No secondary current.

VIII. New form of Interrupter. Curve of secondary current through discharge tube. Peak value of current 98 milliampères. Mean value 14 milliampères. Direct current in primary, 70 volts, 8·0 ampères.

IX. Old form of interrupter. Curve of secondary current through discharge tube. Alternating current in primary. 60 volts, 8·0 ampères.

X. New form of interrupter. Curve of secondary current through X-ray gas bulb. Alternating current in primary. 100 volts, 8·0 ampères. Peak value of secondary current 180 milliampères. Mean value 5 milliampères.